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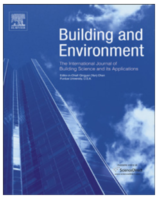

Experimental study of exposure to cooking emitted particles under single zone and two-zone environments

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ABSTRACT

Cooking is a major indoor pollutant source. It is important to know the exposure not only inside but also outside the kitchen. However, the spatial distribution of particle concentration in two indoor zones has not been studied extensively. Therefore, this study investigated particle transport between two zones for a water boiling process under four kitchen hood operation scenarios. Particles were counted using a condensation particle counter; since most of the particles were less than 100 nm in diameter, the study may be considered a study of ultrafine particles. If the range hood operates during the cooking period, or both during and after the cooking period, exposures can be substantially reduced. For the single zone scenario (connecting door closed), operation of the hood during the cooking period reduces exposure by 87–92%, compared to the no-hood operation. When the door between the two zones is opened and the hood is not operated, the exposure in non-kitchen zone ranged from 30% to 54% of that near the stove. Strong exhaust airflow from the kitchen hood interacted with the ventilation airflow, generating complex airflow which resulted in varying concentrations at different points in the kitchen zone. Under the scenario with the range hood off both during and after cooking, comparing at point nearest the stove, the exposure at the other points ranges from 65 to 90% while under the range hood on both during and after cooking scenario, the exposure ranges from 30 to 90%.

1. Introduction

People stay indoors most of their time [1]. In a non-smoking household, cooking is often the major source of pollutants, including aerosols [2–4] and gaseous pollutants [5,6]. A recent article provides an excellent review on aerosol size characteristics and chemical compositions generated by different cooking styles [7]. The authors also commented that Chinese cooking style generates much higher PAHs than western style cooking.

Once emitted, aerosols disperse inside kitchens. In most literature studies a well-mixed condition was assumed or only a single location measurement was taken [8–11]. Other studies only focused on the exposure measurement close to the source [12–14]. This may characterize the exposure of the cook, but not necessarily that of other members of the household. Bhangar et al. [15] measured exposure for 7 houses. They concluded that for indoor-generated particle sources, near-source exposure can be significantly higher.

Some studies have considered concentrations in different zones due to cooking. Rim et al. [11] measured cooking emitted particle concentration in a full-size manufactured house. Concentration levels in the master bedroom and kitchen were measured. However, no inter-zone correlation was proposed. Lai and Chen [16] simulated cooking activity in a flat containing a kitchen and a non-kitchen area. They found that well-mixed concentrations may not be achieved inside kitchens due to the strong local buoyancy effect. Both temperature and concentration profiles showed a large variation in the kitchen and non-kitchen area. Furthermore, the spatial concentration variation in a kitchen was also studied by Lai and Ho [17]. They conducted an experiment in a real residential kitchen and a numerical simulation under a low air exchange condition. Results showed that the concentration could be 3 times higher at a location of 0.3 m from a cooking stove when compared with that sampled at the location of 2.8 m from the cooking stove. These two studies indicated that spatial variation could be found within a single zone (i.e. only kitchen was considered) as well as two-zone micro-environments. Other studies focused on spatial

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variation of particulate matter (PM) in domestic apartments [8,18–21]. They reported that concentration variation could be found between a kitchen and living room, although some studies showed a negligible difference between zones. However, these studies focused on fine and coarse particles. Ultrafine particles (<100 nm) are now of great interest due to their production by cooking with both electric and gas stoves [22]. Wan et al. [10] conducted a field measurement focusing on ultrafine particles in 12 residential homes. The cooking activities were controlled by those residents. The authors measured both the number and mass concentrations in living rooms and kitchens. However, they only reported the 12-site average values without any details of cooking conditions. The status of operation of range hood, cooking style, and cooking duration were not specified and reported. Since those cooking conditions could influence the transport of particles, without this information, it is impossible to calculate exposure at different locations inside a home.

Adverse health effects, such as respiratory symptoms and lung cancer, have been widely reported to be positively associated with exposure to cooking [23–25]. Recent study in Taiwanese families showed that poor ventilation leaded to $PM_{3.2}$ as high as 160 $\mu g/m^3$ [6]. Thus it is essential to reduce exposure to the cooking-generated pollutants. People commonly use domestic kitchen range hoods to maintain better indoor air quality in residential kitchen. Some studies have tested different parameters regarding kitchen hoods, such as exhaust flow rate, distance between stove and hood, front and back burners, etc. They showed that these variables could influence human exposure to cooking pollutants or capture efficiency of the hood [11,26]. In a recent article the authors measured capture efficiency for aerosols by a 6-bins optical particle counter and a condensation particle counter. They found that capture efficiency for gaseous pollutants is different from aerosols, which further complicates the issue [27]. Previous studies and conclusions concerning gaseous pollutants may not be applicable to or validated for aerosols.

There are knowledge gaps on understanding and quantifying exposure inside and outside the cooking zones. Thus the objectives of this study lie in a few areas; (1) studying homogeneity of cooking-generated particles concentration within a single-zone (cooking zone); (2) quantifying the particles transport to the non-cooking zone; (3) influencing of hood operation on exposure.

2. Study design and procedures

2.1. Study design and methodology

An environmental controlled chamber with dimensions 4.6 m (L) × 2.25 m (W) × 2.3 m (H) was used as a mock-up for performing our cooking activities. The chamber is divided into two equal volume zones, named as kitchen zone and non-kitchen zone, each 2.3 m in length. A door of dimension 0.9 m (W) × 2 m (H) is located at the partition such that closing this door can separate the two zones. The chamber is made of stainless steel with very smooth surfaces. A well-mixed (WM) ventilation system was operated throughout the study, where the air exchange rate was set to be 6 h^{-1}. Before starting the experiments, leakage test was conducted. Differential pressure of 20 Pa was applied and measured by a manometer when CO_2 was simultaneously injected to the room. Analysis of the CO_2 decay plot yielded the leakage rate, which is approximately 0.1 ACH under the specified pressure difference of 20 Pa and can be ignored compared to the supply air rate.

A new, non-commercial grade domestic kitchen range hood with the dimension of 0.7 m (L) × 0.525 m (W) × 0.135 m (H) was selected. The range hood was installed at a height of 1.58 m inside the kitchen zone of the chamber, 0.75 m above the cooking stove. The height is within the range of distance of 60–90 cm above the cooking stove recommended by the manufacturer. Fig. 1 shows the three-dimensional installation plan of the domestic kitchen hood. An exhaust air duct was connected to the space outside the environmental chamber. The air was filtered by a HEPA filter before it discharged to the laboratory. As the real exhaust flow rate would be affected by the length of exhaust air duct and the additional HEPA filter, the flow rate of operation of the single exhaust fan was measured after the complete installation of the kitchen hood. The velocities at 9 points at the outlet of exhaust air duct were measured by a hand-held hot-wire anemometer (9555, TSI; accuracy of ±3%). There are three exhaust airflow settings; low, medium and high. In this study, the exhaust flow rate is not the focus and hence, only one exhaust flow rate (the lowest setting) was set throughout experiments. As the chamber is not large, the lowest exhaust flow rate was expected to provide sufficient performance on exposure reduction. It is calculated using Eq. (1) and found to be 483.6 m^3/h.

$$Q = \overline{V}A \tag{1}$$

where Q is the exhaust flow rate, $\overline{V}$ and A are the 9-point-averaged velocity and the cross-section area of the exhaust air duct respectively. The equivalent ACH of the hood is 41 h^{-1}. It can be anticipated that this high airflow would interfere with ventilated airflow when operated. Results support this observation.

To study dispersion inside a single zone and transport between two zones, two types of door scenarios were conducted: door closed or opened (Fig. 2). For the experimental set focusing on dispersion in a room (single zone), the door connecting the two zones was closed. Thus all points except sampling point F would not be measured. For the experimental set focusing on particle intertransport study (two-zone), the door was opened, and all the sampling points were measured. It should also be noted that only water boiling was used for this study. Location A is very close to the stove, if oil were used, it would anticipated that very high concentration, sticky particles were sampled and they may affect the optics of the CPC.

The influence of hood performance on cooking-emitted particle concentration was investigated by 4 hood operation scenarios. The kitchen hood was operated for 4 scenarios under each experimental condition: (i) hood turned off (off-off); (ii) hood off during cooking, on after cooking (off-on); (iii) hood on during cooking, then off (on-off) and (iv) hood always on (on-on).

The concentrations at a total of 6 sampling points were measured. Five of them were located in the kitchen zone, while one sampling point was located in the non-kitchen zone. The detailed locations of the sampling points are listed in Table 1. All sampling points were located at a height of 1.55 m, representing the breathing zone of people.

The selection of locations needed elaboration. Location A mimics the location of a cook. It was chosen because it represents the possible exposure of a cook and likely the practical maximum exposure inside the cooking zone. Location B is chosen to represent a person far away from the stove. Location C is at the center point and the result can be taken as an average exposure. Location D represents a position near the door connecting to the non-cooking zone. It was chosen in order to understand how particles transport to the non-cooking zone. E is at the location under the supply air. It mimics the exposure for a person standing near the mechanical supply diffuser with clean air delivered. F is the location in the non-cooking zone. It mimics exposure of an occupant staying in the zone during the entire cooking period. Overall speaking the selections of these locations supporting the objectives of the study.